NeoBiota 90: 139–159 (2024)
doi: 10.3897/neobiota.90.112368
https://neobiota.pensoft.net

RESEARCH ARTICLE

A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

Field studies of the ecological impacts of invasive plants in Europe

Montserrat Vilà[1,2], Alejandro Trillo[1], Pilar Castro-Díez[3], Belinda Gallardo[4], Sven Bacher[5]

1 *Estación Biológica de Doñana (EBD-CSIC), 41092 Sevilla, Spain* **2** *Department of Plant Biology and Ecology, Universidad de Sevilla, 41012 Sevilla, Spain* **3** *Universidad de Alcalá, Facultad de Ciencias, Departamento de Ciencias de la Vida, Área Ecología, Grupo de Investigación en Invasiones Biológicas, Campus Científico-Tecnológico, E-28805, Alcalá de Henares, Madrid, Spain* **4** *Applied and Restoration Ecology Group, Pyrenean Institute of Ecology (IPE-CSIC), 50059 Zaragoza, Spain* **5** *University of Fribourg, Department of Biology, Unit of Ecology and Evolution, 1700 Fribourg, Switzerland*

Corresponding author: Montserrat Vilà (montse.vila@ebd.csic.es)

Academic editor: Sven Jelaska | Received 7 September 2023 | Accepted 24 December 2023 | Published 25 January 2024

Citation: Vilà M, Trillo A, Castro-Díez P, Gallardo B, Bacher S (2024) Field studies of the ecological impacts of invasive plants in Europe. NeoBiota 90: 139–159. https://doi.org/10.3897/neobiota.90.112368

Abstract

The impacts of invasive species can vary widely across invaded sites and depend on the ecological variable of study. In this paper, we describe the first harmonised database that compiles scientific evidence of the ecological impacts of invasive plant species at continental scale. We summarise results from 266 publications reporting 4259 field studies on 104 invasive species in 29 European countries. For each study, we recorded whether the effects were statistically significant and noted their direction (i.e. decrease or increase in the response variable when compared to uninvaded sites). We classified studies, based on the impacts on the levels of ecological organisation (species, communities and ecosystems), taxa and trophic level. More than half of the studies were conducted in temperate and boreal forests and woodlands and temperate grasslands. Notably, one third of the studies focused on just five invasive species. Most studies were on native species followed by studies on communities. Impacts on plants were more frequently studied than impacts on other taxa and trophic groups. Overall, 43% of the studies reported significant impacts, with more significant decreases (26%) than increases (17%) in the response variables. Significant impacts were more frequent on species and communities than on ecosystems; and on plants than on animals or microbes. This database is of interest for academic, management and policy-related purposes.

Keywords

Biological invasions, context-dependence, diversity, ecological organisation, ecosystem properties, European Regulation on IAS, non-native plants, trophic level

Introduction

Many non-native species introduced by human agency outside their original area of distribution invade natural areas and cause ecological impacts to native species, communities and ecosystems (Simberloff et al. 2013). Ecological impacts are defined in this paper as any statistically significant ecological change occurring when an invasive species is present compared to when the invasive species is absent. This change can be a decrease (i.e. negative impact) or an increase (i.e. positive impact) of any ecological attribute of the invaded ecosystem (Jeschke et al. 2014). Thus, it is important to note that negative and positive impacts are independent of ethical and societal human values (Vimercati et al. 2020).

Information on the impacts of invasive species is of fundamental importance to assist management and policy (Vilà et al. 2019). In particular, empirical studies of ecological impacts provide essential scientific evidence to underpin risk assessment of invasions that are often used to rank and prioritise management actions. Despite the fast increase in the number of field studies testing for invasive species impacts, the majority focus on a few species and regions. Consequently, there are still important biases and gaps in knowledge that preclude our capacity to provide information for management and policy actions (IPBES 2023). It is thus of paramount importance to synthesise the scientific evidence on impacts to identify which are the most studied invasive species, the most studied habitats and the most studied impact types.

Meta-analyses have shown a strong context-dependency not only in the magnitude, but also in the direction of the impacts (Pyšek et al. 2012; Gallardo et al. 2016; Volery et al. 2021; Romero-Blanco et al. 2023). For example, an invasive N-fixing plant may strongly increase soil fertility in a recipient ecosystem with N-deficient soils and lacking native N-fixing species, but may have negligible impacts in communities including native N-fixing plants or in soils otherwise rich in N (Vitousek and Walker 1989; Castro-Díez et al. 2014, 2016). Moreover, invasive species can cause multiple, sometimes contrasting, impacts at different levels of ecological organisation (species, communities and ecosystems). For example, an invasive N-fixing plant may increase N soil availability and this can favour the establishment of some native plant species at the expense of others, with a neutral effect on species richness (Marchante et al. 2011). Thus, the impact of an invasive species can vary, presenting a neutral, negative or positive effect. This variability depends on factors such as the identity of the native species under study or whether the focus is on particular native species or the entire community. Therefore, to guide management decisions and biodiversity conservation efforts, it is important to document a broad spectrum of numerical increases and decreases in ecological responses following invasion. Given the conservation interest in native species and communities, adopting a value-laden perspective, their decrease may be considered deleterious, while an increase may be considered beneficial (Vimercati et al. 2020).

The environmental assessment of the impacts of invasive species requires the analysis of the full range of ecological changes after invasion. To this end, we conducted a comprehensive review of field studies reporting ecological impacts of invasive plant species in Europe to identify the most studied species, countries and habitats and to describe the frequency and direction of impacts. We classified impacts according to four

criteria: i) the ecological level at which the impact is measured, i.e. species, communities and ecosystems; ii) the affected taxonomic level, i.e. microbes, plants and animals; and iii) the trophic level of the affected taxa. Beyond identifying the most-studied invasive plant species and habitats and their most-studied impacts, our database also enables the exploration of differences in the frequencies and directions of impact types studied. Specifically, we explored if there were differences in the frequency of impacts amongst levels of organisation and taxa.

Material and methods

We started from the studies conducted in Europe extracted from the databases constructed and analysed in Pyšek et al. (2012) and in Castro-Díez et al. (2019). Additionally, we searched for new publications on the Web of Science (https://www.webofscience.com/wos/alldb/basic-search) database on 31 December 2022 with no restriction on publication year, using the following search term combinations: (plant inva* OR exotic plant OR alien plant OR non-native plant) AND (impact* OR effect*) AND (community structure* OR diversity* OR ecosystem process* OR competition*). Amongst the retrieved documents, we first screened titles and abstracts to identify all publications on the impacts of invasive plants conducted in Europe. We then examined each publication and constructed a database of impacts according to the following selection criteria:

1. The studies had to be in natural or semi-natural field conditions in Europe. The habitat type of the study was classified according to the IPBES unit of analysis (IPBES 2018) with the exception that, in this study, coastal areas was considered for terrestrial plants. The evidence of impact was based on observational or experimental (i.e. removal or addition of target species) field studies comparing simultaneously invaded or uninvaded sites where the identity of single invasive species of study was explicitly mentioned. We excluded tree plantations. We also excluded those referring to impacts by several invasive species.
2. When the same publication examined different response variables, different invasive species, different ecosystem types or geographically different localities, we considered each as different entries in the database (i.e. study, hereafter).
3. When a response variable was measured at different times (e.g. sampling species diversity across years), we made an informed decision on whether to take the mean value across times or to consider each measure as independent. However, when the variable was repeated across short periods (e.g. sampling N availability in different weeks), we only used the final measurement or the most representative (e.g. when the soil activity was the highest).
4. When the study manipulated other environmental factors in addition to invasion, we only considered results from the non-manipulated plots.
5. When the study investigated the effects of different degrees of invasion and different residence times (i.e. old vs. recent invasions), we examined differences between the least invaded sites and the most invaded sites and differences between uninvaded sites and sites with the longest time since invasion.

As all studies dealt with established non-native plant species and their threats to biological diversity and/or ecosystems, for simplicity, we refer to them as "invasive species" through out the text.

Following Vilà et al. (2011), impacts were classified according to the affected level of ecological organisation as follows: impacts to native species (e.g. abundance, performance, biomass), to communities (e.g. abundance, biomass or diversity) and to ecosystem properties (e.g. soil C/N, nutrient fluxes, decomposition rates, pH, nutrient pools, resource availability, soil minerals, soil organic matter and soil salinity/cation exchange capacity) (Table 1, Suppl. material 1: table S1). Furthermore, when the information was available, the impacts to species and communities were also classified according to the affected taxa (i.e. microbes, plants and animals) and to the trophic level of the affected taxa (i.e. impacts to herbivores, parasites, plants, pollinators, predators, omnivores, decomposers and symbionts) (Table 2). If the native species of concern belongs to different trophic levels along its life history, we considered the one during the stage of the study. In total, the database considered 23 impact types, which integrate the main biodiversity and ecosystem changes after invasion and allow for comparing impacts across studies (see Tables 1, 2).

For each impact, we recorded the statistical significance (no/yes) and direction (increase/decrease) of differences between invaded and uninvaded plots. For the purpose of this analysis, the direction does not mean a desirable/undesirable impact, but a significant increase or decrease of the response variable analysed in the invaded compared to the uninvaded control treatment, respectively.

To search for differences in the frequency of significant impacts across different levels of organisation (species, community, ecosystem) and taxa (animals, microbes, plants), we summed the number of responses – whether significant or non-significant – for each impact type. Responses were grouped, based on the identity of the invasive species and the respective publication.

We employed generalised linear mixed models (GLMMs) with a binomial (logit link function) error distribution family (lmerTest package; Kuznetsova et al. (2017)). The response variable was a two-column matrix generated using the 'cbind' function to combine the counts of significant and non-significant impacts. In each model, we included as a fixed factor the levels of ecological organisation or taxa. To account for the non-independence of data, we included the publication and the identity of the invader as random factors. Post-hoc Tukey tests (emmeans package; Russell (2018)) were then applied to evaluate differences in impact frequencies amongst levels of ecological organisation and taxa. To visualise these differences, we used the package ggeffects (Lüdecke 2018). All analyses were performed in R (v. 4.2.1, R Core Team (2022)).

Open research statement

All data employed in this research are archived in Figshare repository https://doi.org/10.6084/m9.figshare.23579082.

Table 1. Ecological impacts of invasive plant species studied in field conditions in Europe classified by categories of ecological organization (species, communities, ecosystems), with indication of the response variables examined in the literature. In parenthesis, the sample size (number of field studies testing for impacts). See Table S1 for definitions of the impact type classification.

Level of ecological organization	Impact type	Variables related to
Species (576)	Animal (176)	Animal abundance (143), activity (10), fitness (4), performance (19)
	Microbial (5)	Microbial abundance (5)
	Plant (395)	Plant abundance (223), biomass (34), fitness (66), performance (72)
Community (2541)	Animal (1142)	Animal abundance (682), activity (3), biomass (11), diversity (446)
	Microbial (370)	Microbial abundance (111), activity (150), biomass (17), diversity (92)
	Plant (1016)	Plant abundance (254), biomass (130), diversity (632)
Ecosystem (1155)	Soil carbon to nitrogen ratio (C/N) (74)	C/N (74)
	Nutrient fluxes (25)	C fluxes (11), N fluxes (14)
	Decomposition rates (39)	Litter decomposition (38), soil organic matter mineralization (1)
	pH (134)	pH (134)
	Nutrient pools (402)	C pools (114), N pools (194), P pools (94)
	Resource availability (83)	Light (19), moisture (60), soil temperature (4)
	Soil minerals (264)	Soil minerals (264)
	Soil organic matter (85)	Soil organic matter (85)
	Soil salinity/cation exchange capacity (CEC) (49)	Soil CEC (1), salinity (3), salinity/CEC (45)

Table 2. Ecological impacts of invasive plant species studied in field conditions in Europe classified by the trophic level of affected species (i.e. decomposers, herbivores, omnivores, parasites, plants, pollinators, predators, symbionts) with indication of the response variables examined in the literature. In parenthesis, sample size (number of field studies testing for impacts).

Trophic level of the affected taxa	Variables related to
Decomposer (269)	Decomposer abundance (189), biomass (7), diversity (62), activity (11)
Herbivore (100)	Herbivore abundance (62), diversity (36), performance (2)
Omnivore (47)	Omnivore abundance (41), diversity (3), fitness (2), performance (1)
Parasite (50)	Parasite abundance (44), biomass (2), diversity (4)
Plant (1411)	Plant abundance (477), biomass (164), diversity (632), fitness (66), performance (72)
Pollinator (353)	Pollinator abundance (190), activity (9), diversity (142), fitness (2), performance (10)
Predator (287)	Predator abundance (224), activity (4), biomass (1), diversity (54), performance (4)
Symbiont (23)	Symbiont abundance (16), biomass (1), diversity (6)

Results

Our final database included 266 publications describing 4259 field studies of 104 invasive plant species in Europe (Fig. 1, Suppl. material 1: tables S2, S3).

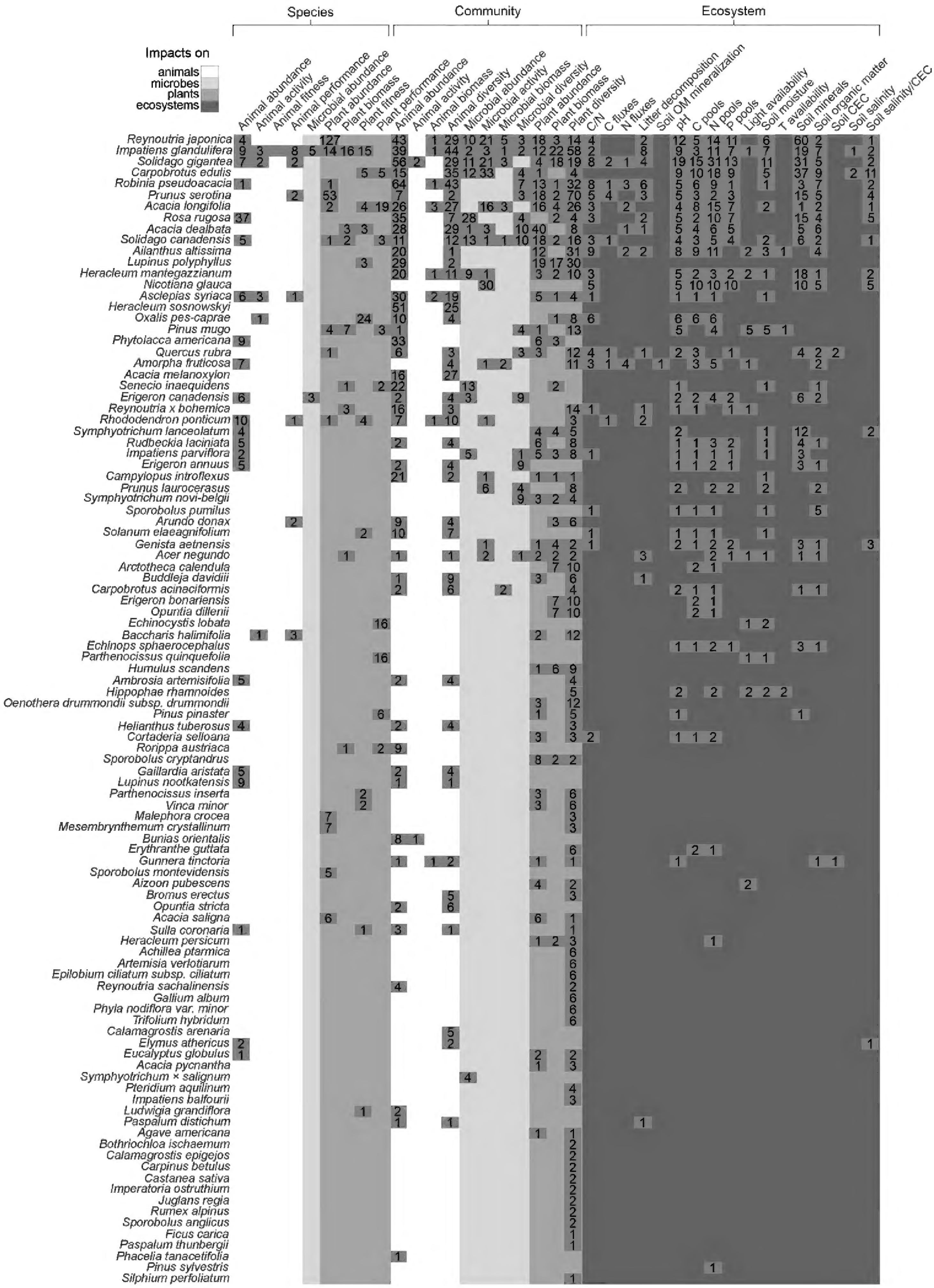

Figure 1. Total number of field studies testing for impacts in Europe classified by invasive plant species, ecological organisation and impact type. The grey shading legend indicates whether the impact is on animals, microbes, plants or ecosystems.

Impacts of invasive plants are widely studied across Europe, although around 50% of studies were carried out in six countries (Spain, Poland, Czech Republic, Germany, Italy and Portugal) and there are some countries without any studies (e.g. Albania, Bulgaria, Estonia and Latvia) (see Fig. 2). Most studies were conducted in temperate and boreal forests and woodlands (33%) and temperate grasslands (26%), followed by coastal areas (14%) and Mediterranean forests and woodlands (12%) (Fig. 3).

Figure 2. Map of locations (red dots) of field studies on the ecological impacts of invasive plant species in Europe. Twelve publications described studies in multiple countries and were represented by a dot in each country.

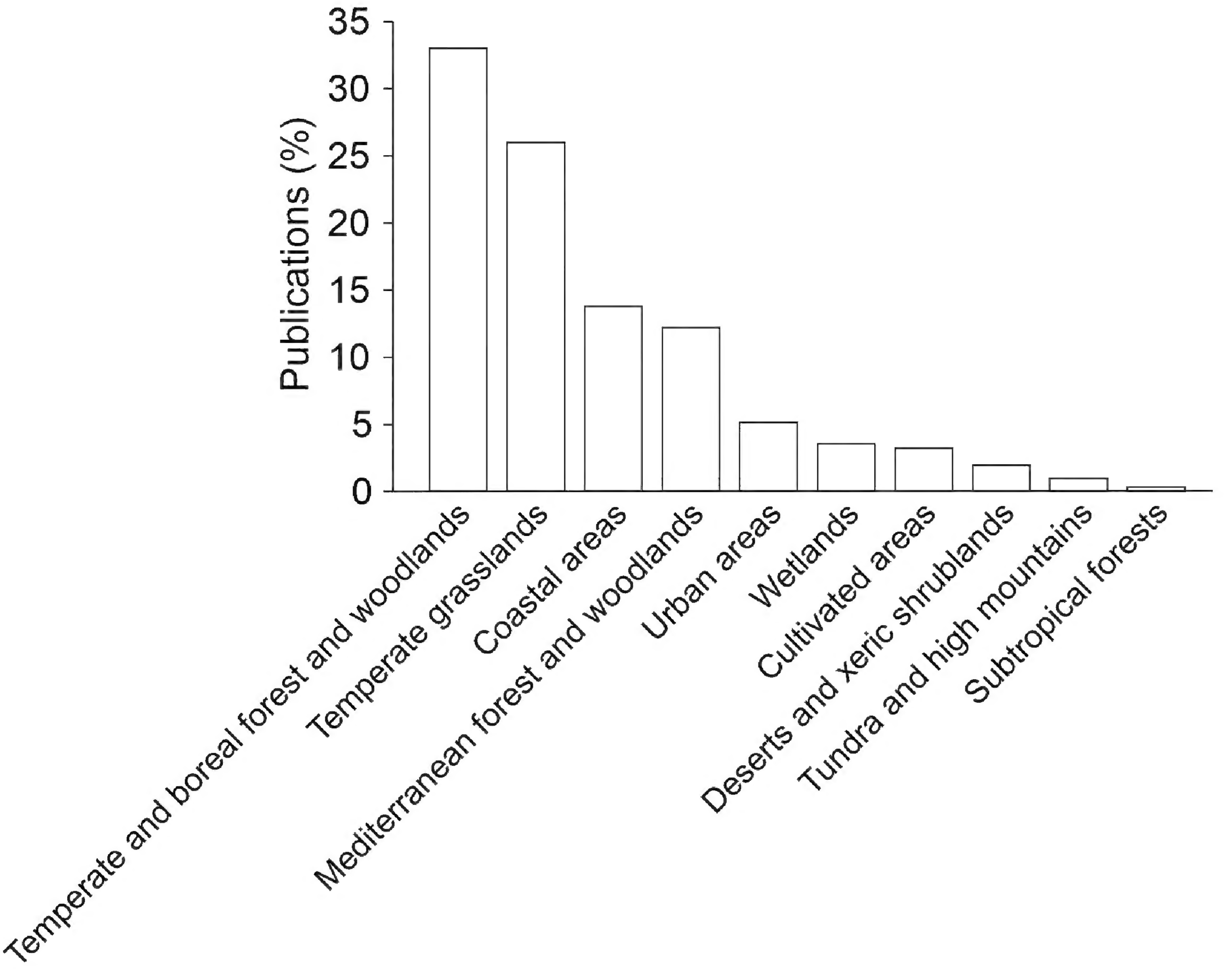

Figure 3. Percentage of publications on field studies testing for impacts classified by the invaded habitat in Europe. Habitats were classified according to the IPBES unit of analysis (IPBES 2018).

While the number of invasive plant species studied has increased linearly since about 2005, the number of publications on impacts have increased exponentially (Fig. 4a). One third of the publications examined the impacts of only five species (*Reynoutria japonica*, *Impatiens glandulifera*, *Solidago gigantea*, *Carpobrotus edulis* and *Robinia pseudoacacia*) out of 104 (Fig. 5). The studies on these five species have been concentrated in the last two decades and are still increasing to date (Fig. 4b).

The most studied impacts are on the abundance of species followed by impacts on the abundance and diversity of communities. Impacts on plants have been more studied than impacts on other taxa and trophic groups (Fig. 6). The second most studied impacted group is that of pollinators, followed by predators and decomposers (Fig. 6d). Impacts on microbial communities, although less frequently studied, have increased in the last few years (Fig. 6b). The number of field studies testing for impacts to ecosystem properties have increased one order of magnitude in the last decade (Fig. 4c), with impacts on nutrients pools and soil minerals being the most common (Fig. 6c).

Overall, 43% of studies found significant impacts of invasive plants with more decreases (26%) than increases (17%) on the response variables. Although more than half of the species (58 out of 104) have impacts in both directions, 10% of the invasive species showed only increase responses and 30% decrease responses (Fig. 5).

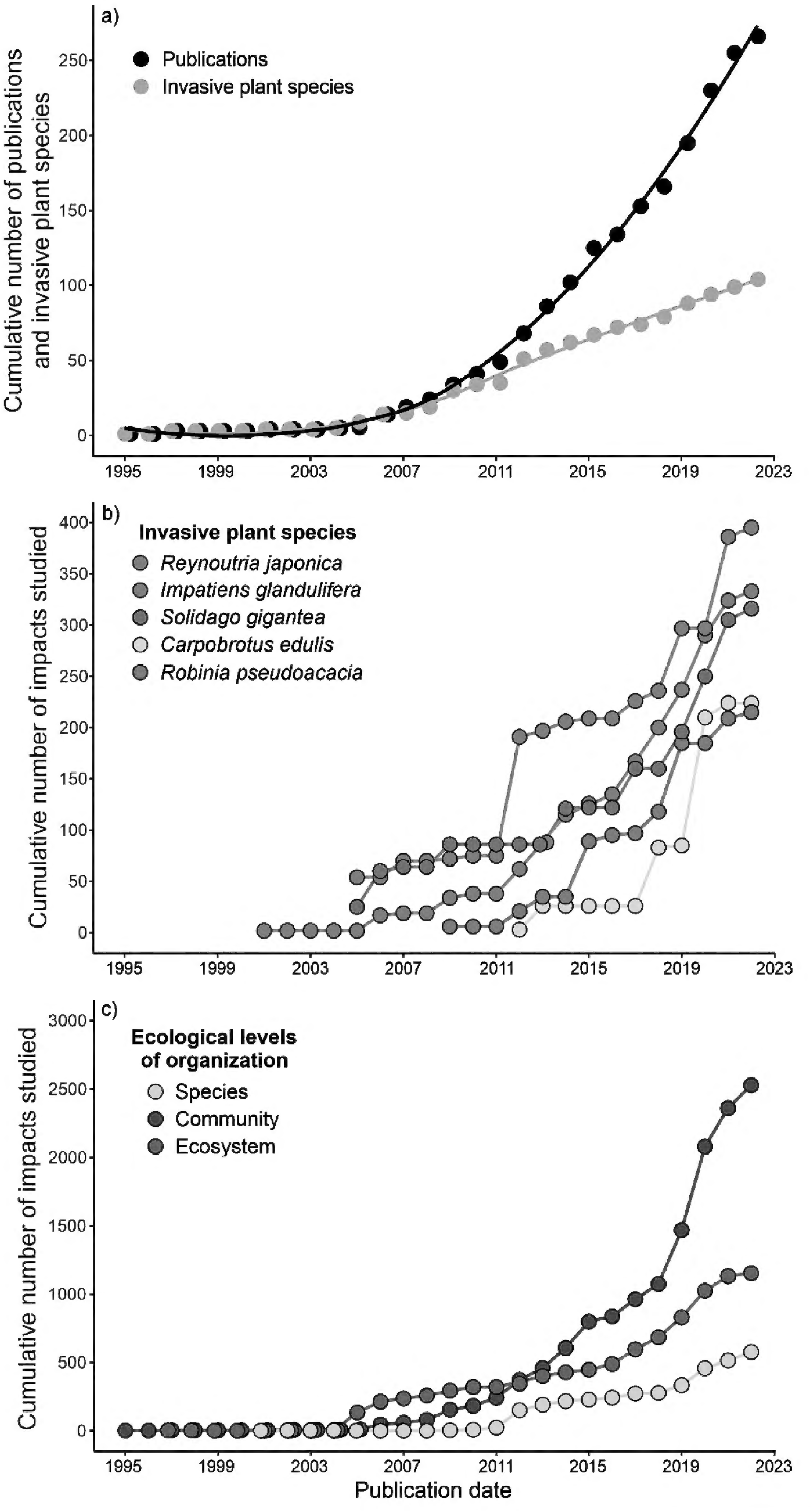

Figure 4. Cumulative total number of publications on impacts and invasive plant species studied (**a**), number of field studies testing for impacts on the five most studied species (**b**) and across ecological levels of organisation (**c**) in Europe. See Table 1 for impact type classification.

Invasive plant species	Studies	Publications	Frequency (%)
Reynoutria japonica	395	19	39.2
Impatiens glandulifera	333	35	40.2
Solidago gigantea	316	21	39.6
Carpobrotus edulis	224	9	45.1
Robinia pseudoacacia	215	19	41.9
Prunus serotina	206	12	33.5
Acacia longifolia	191	13	66.5
Rosa rugosa	170	7	38.8
Acacia dealbata	158	9	50.0
Solidago canadensis	126	14	41.3
Ailanthus altissima	115	12	47.8
Lupinus polyphyllus	100	11	41.0
Heracleum mantegazzianum	96	8	30.2
Nicotiana glauca	90	1	44.4
Asclepias syriaca	76	8	13.2
Heracleum sosnowskyi	76	4	63.2
Oxalis pes-caprae	72	4	27.8
Pinus mugo	53	7	71.7
Phytolacca americana	51	1	35.3
Quercus rubra	48	4	29.2
Amorpha fruticosa	46	5	43.5
Senecio inaequidens	43	3	37.2
Acacia melanoxylon	43	1	60.5
Erigeron canadensis	42	3	2.4
Reynoutria x bohemica	42	4	59.5
Rhododendron ponticum	41	7	36.6
Symphyotrichum lanceolatum	40	3	40.0
Rudbeckia laciniata	38	4	28.9
Impatiens parviflora	35	6	40.0
Erigeron annuus	29	2	6.9
Campylopus introflexus	28	3	82.1
Prunus laurocerasus	28	1	35.7
Symphyotrichum novi-belgii	27	4	18.5
Sporobolus pumilus	25	2	64.0
Solanum elaeagnifolium	24	4	12.5
Arundo donax	24	2	50.0
Genista aetnensis	23	2	91.3
Acer negundo	22	6	68.2
Carpobrotus acinaciformis	20	5	45.0
Buddleja davidii	20	3	30.0

Figure 5. List of invasive plant species with the total number of field studies testing for impacts, publications and impact frequency (i.e. percentage of significant responses). Blue and orange bars indicate the proportion of decreases and increases, respectively.

Arctotheca calendula	20	2	50.0
Erigeron bonariensis	20	2	40.0
Opuntia dillenii	20	2	40.0
Echinocystis lobata	19	1	31.6
Baccharis halimifolia	18	3	83.3
Echinops sphaerocephalus	18	1	11.1
Parthenocissus quinquefolia	18	1	44.4
Humulus scandens	16	1	31.3
Ambrosia artemisiifolia	15	3	0.0
Hippophae rhamnoides	15	1	0.0
Oenothera drummondii drummondii	15	1	46.7
Pinus pinaster	14	1	57.1
Helianthus tuberosus	13	3	7.7
Cortaderia selloana	12	2	83.3
Rorippa austriaca	12	1	66.7
Sporobolus cryptandrus	12	1	75.0
Gaillardia aristata	11	1	18.2
Lupinus nootkatensis	11	1	72.7
Parthenocissus inserta	11	1	100.0
Vinca minor	11	1	90.9
Malephora crocea	10	1	60.0
Mesembrynthemum crystallinum	10	1	50.0
Gunnera tinctoria	9	3	100.0
Erythranthe guttata	9	2	44.4
Bunias orientalis	9	1	66.7
Sporobolus montevidensis	9	1	33.3
Opuntia stricta	8	2	12.5
Bromus erectus	8	1	75.0
Aizoon pubescens	8	1	100.0
Sulla coronaria	7	2	71.4
Acacia saligna	7	1	28.6
Heracleum persicum	7	1	85.7
Reynoutria sachalinensis	6	2	100.0
Achillea ptarmica	6	1	100.0
Artemisia verlotiarum	6	1	66.7
Epilobium ciliatum subsp. ciliatum	6	1	66.7
Gallium album	6	1	16.7
Phyla nodiflora var. minor	6	1	83.3
Trifolium hybridum	6	1	33.3
Elymus athericus	5	2	100.0
Ulmus pumila	5	2	80.0
Calamagrostis arenaria	5	1	60.0

Figure 5. Continued.

Acacia pycnantha	4	1	100.0
Symphyotrichum × salignum	4	1	100.0
Pteridium aquilinum	4	1	50.0
Sorbaria sorbifolia	4	1	75.0
Impatiens balfourii	3	1	66.7
Ludwigia grandiflora	3	1	33.3
Paspalum distichum	3	1	33.3
Agave americana	2	1	50.0
Bothriochloa ischaemum	2	1	100.0
Calamagrostis epigejos	2	1	100.0
Carpinus betulus	2	1	100.0
Castanea sativa	2	1	50.0
Imperatoria ostruthium	2	1	50.0
Juglans regia	2	1	100.0
Rumex alpinus	2	1	100.0
Sporobolus anglicus	2	1	100.0
Ficus carica	1	1	100.0
Paspalum thunbergii	1	1	0.0
Phacelia tanacetifolia	1	1	100.0
Pinus sylvestris	1	1	100.0
Silphium perfoliatum	1	1	0.0
Xanthium orientale var. albinum	1	1	0.0

Figure 5. Continued.

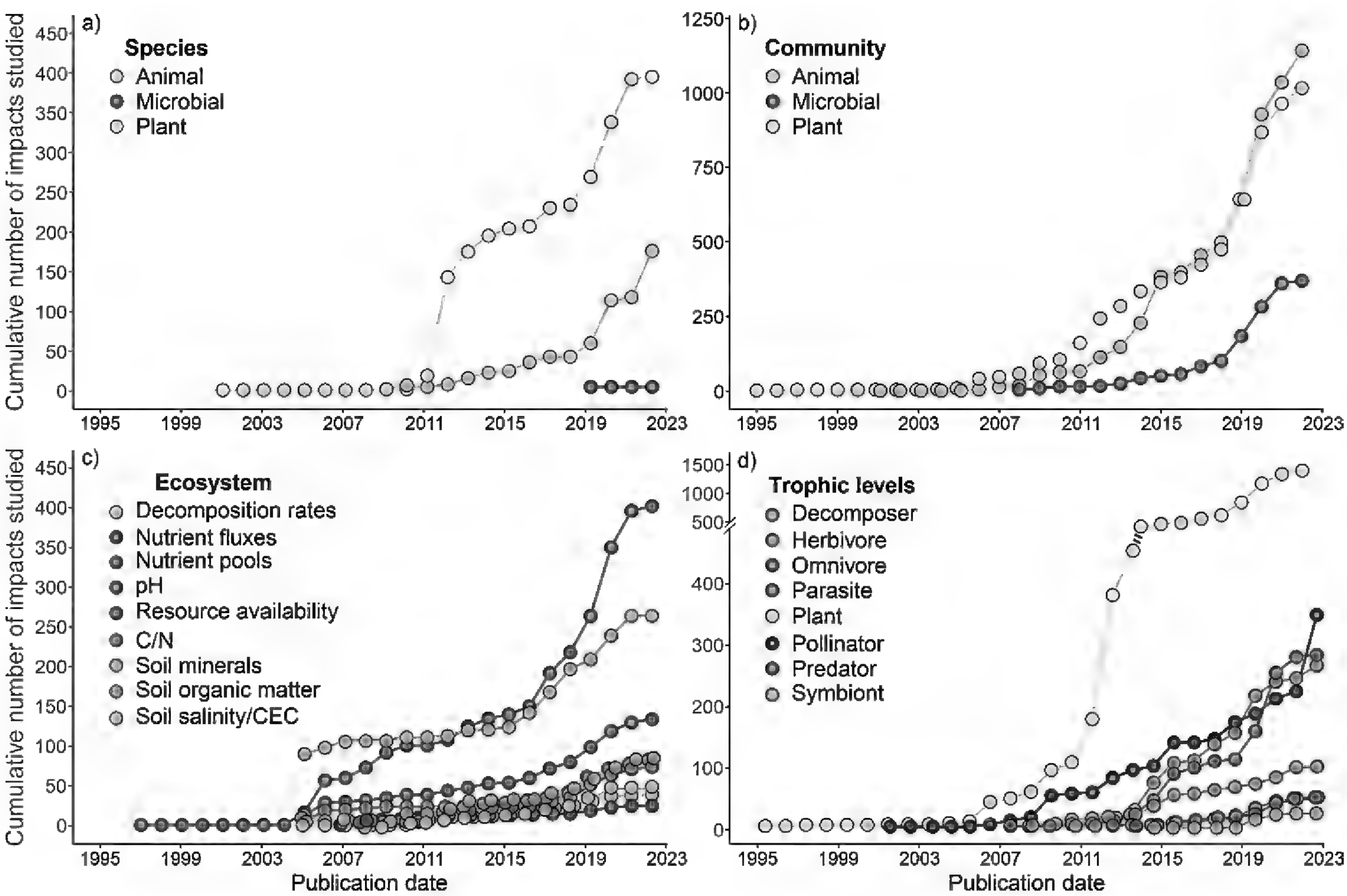

Figure 6. Cumulative number of field studies testing for impacts to species (**a**) and communities (**b**) by taxa, ecosystem properties (**c**) and amongst trophic levels (**d**) in Europe. See Tables 1, 2 for impact type classification.

Results on the frequency of significant impacts and their direction can be found in Fig. 7. In studies where the affected level is species, 41% of the impacts (n = 576) were significant, with more decreases (25%) than increases (16%) on the response variables. At the community level, 47% of impacts (n = 2528) were significant, with two times more decreases (32%) than increases (15%). At the ecosystem level, 38% of impacts (n = 1155) were significant, with fewer decreases (15%) than increases (23%). When impacts were classified by the affected trophic levels, altogether 45% of impacts (n = 2807) were significant, with two times more decreases (30%) than increases (15%).

The frequency of significant impacts was similar between the species and community levels ($z=0.17$, $p= 0.99$), but higher than at the ecosystem level ($z=2.32$, $p = 0.05$ and $z = 3.94$, $p < 0.001$, respectively). Additionally, the frequency of significant impacts was similar between animals and microbes ($z=0.17$, $p=0.99$), but lower than for plants ($z=3.86$, $p< 0.001$ and $z=2.94$, $p< 0.01$, respectively) (Fig. 8).

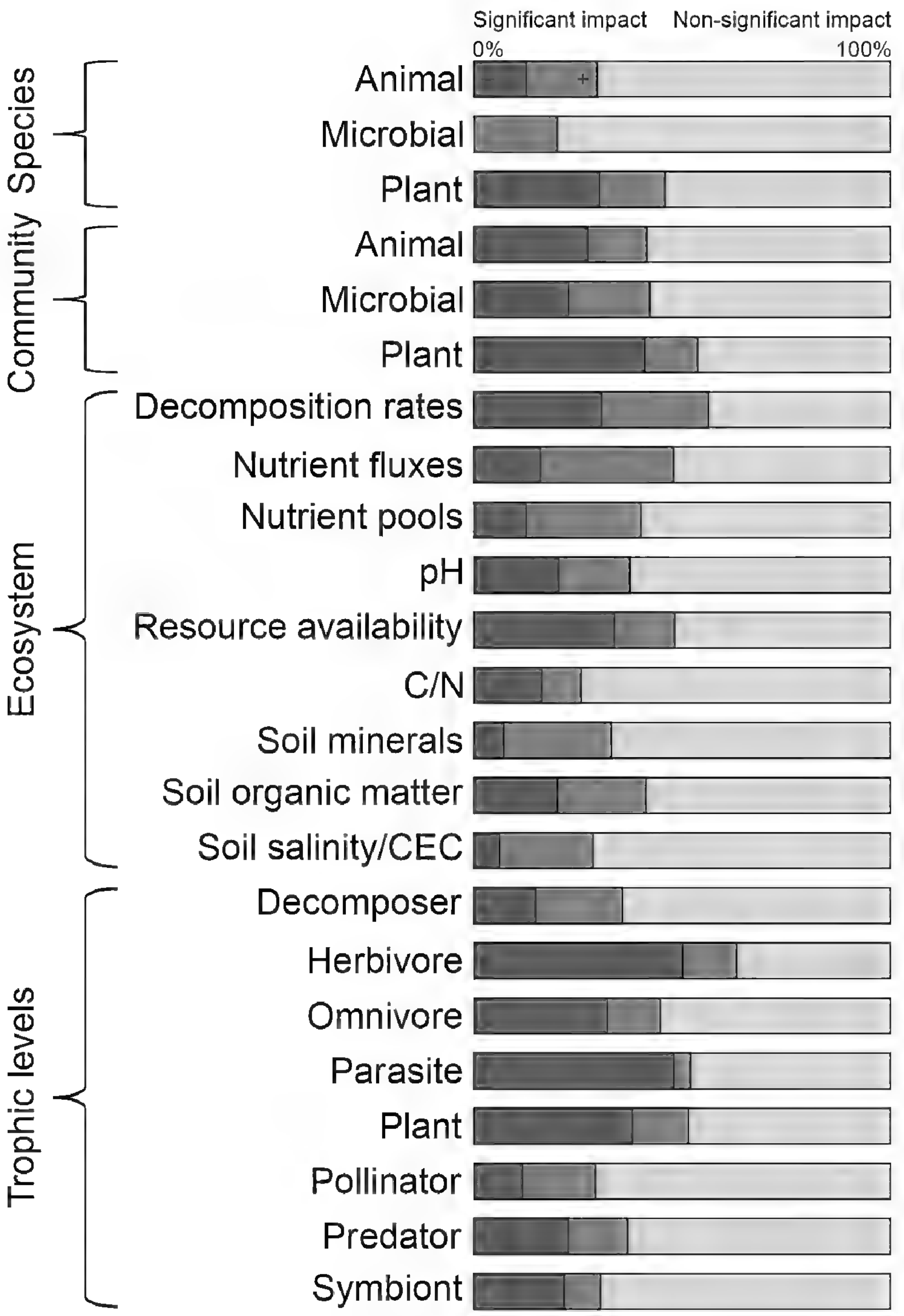

Figure 7. Frequency of significant plant invader impacts vs. percentage of non-significant impacts (grey bars) studied in field conditions in Europe. Blue and orange bars indicate the percentage of decreases and increases, respectively. See Tables 1, 2 for impact type classification.

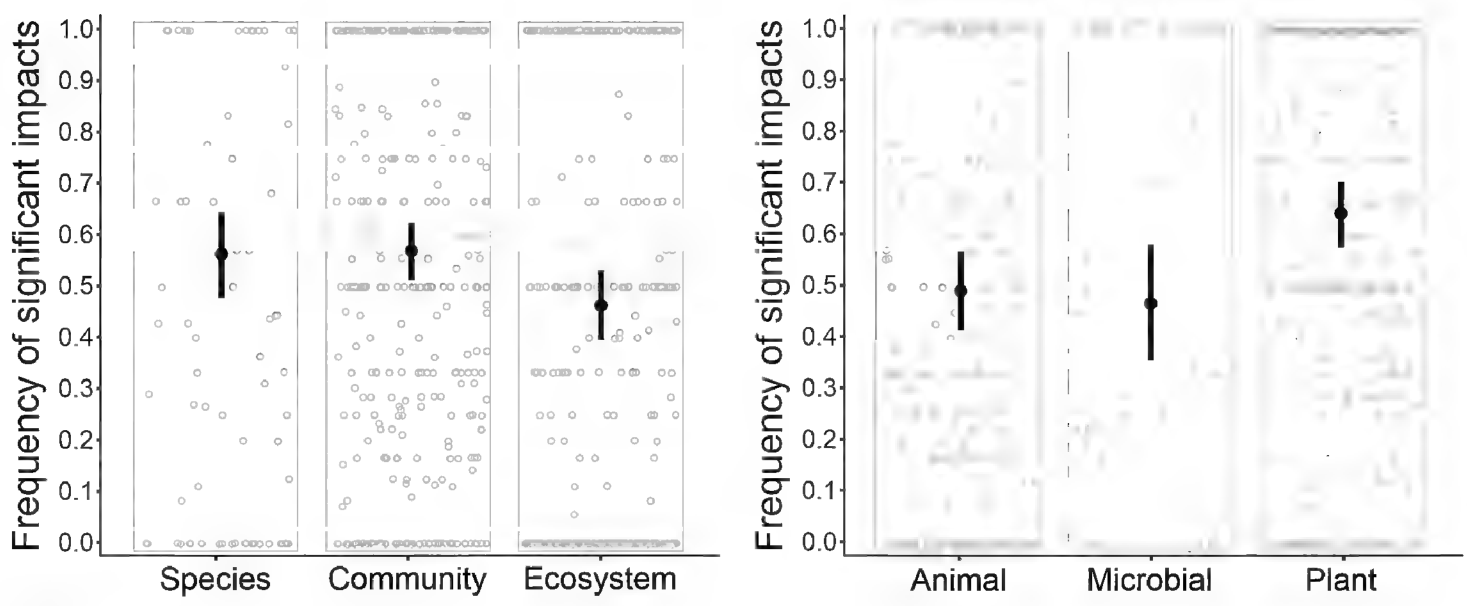

Figure 8. Frequency of significant plant invader impacts studied in field conditions in Europe across levels of ecological organisation (left) and taxa (right). Open circles are observed values (i.e. the proportion of significant impacts grouped by invader species and publication). Black dots are predicted values obtained from the models and their 95% confidence intervals.

Discussion

Evidence about the impacts of invasive plants on different properties of the recipient ecosystems is scattered across many different studies and technical reports (Kumschick et al. 2015), preventing its efficient transfer to managers and policy-makers. Here, we provide the first harmonised database synthesising results from field studies about the ecological impacts of invasive plants at a continental scale. However, a great proportion of studies focuses on a few invasive species in temperate central European countries or in southern Mediterranean countries. As already indicated ten years ago (Hulme et al. 2013), bias continues to be the norm in the study of impacts, probably reflecting the academic interest of research groups on the most common species in their countries. This database can be of scientific, management and policy use at different national and international scales.

The exploration of impact studies indicates that the main geographic gap of knowledge in Europe corresponds to Baltic and Balkan countries. The least represented habitats in impact studies are desert and xeric shrublands, high mountains and subtropical forests. In Europe, subtropical forests of major conservation status are located in Macaronesian islands, where non-native species invasion is prevalent. Many of these islands exhibit a higher proportion of non-native than native plant species in their flora (Kueffer et al. 2010), emphasising the crucial need to identify invasive species causing major impacts (Silva et al. 2008). The impacts of invasive plants in desert and semi-arid habitats are also poorly studied, despite an increasing number of dry-tolerant invasive plants promoted by ornamental xero-gardening (Morente-López et al. 2023). In the face of climate change, it is also imperative to focus more on the impacts of invasive plants in mountain regions. Climate warming is expected to enhance the dispersal and establishment of invasive species at higher altitudes, making this an area of critical concern (Carboni et al. 2018).

Ecological impacts were statistically heterogeneous in their significance and direction. Significant impacts were more frequent on species and communities than on ecosystems. Any change in ecosystem properties can be considered adverse, as it modifies ecosystem functioning (Strayer 2012; Vilà and Hulme 2017; Castro-Díez et al. 2019). Compared to impacts on ecosystems, the impacts on species and communities are more directly linked to changes in biodiversity. According to our database, there were two times more studies reporting negative effects than positive effects on the studied species and community response variables. Negative effects indicate a decrease in native species abundance, fitness or diversity after invasion and are, therefore, considered detrimental for nature conservation. On the contrary, positive effects indicate the reverse and, thus, can be assumed to be beneficial. However, even increasing effects on native species and communities can have cascading effects, depending on the position of the native species in the trophic network (Gallardo et al. 2016).

While the correspondence from value-free to value-laden effects of invaders on biodiversity is not always straightforward (Vimercati et al. 2020), our database on impacts studied in Europe contributes significantly to the global assessment on impacts of invasive species. This comprehensive database aligns with the broader finding that invasive species globally tend to cause more harm than benefits on nature (Bacher et al. 2023).

Significant impacts were more frequently reported on native plants than on native animals or microbes. In general, it seems that invasive species most frequently impact native species from the same broad taxonomic group (Bacher et al. 2023). For plants, this is an expected result because the main mechanism of interaction amongst plants is resource competition or facilitation, while the mechanisms of impact of invasive plants on animals are more diverse and often indirect, depending on the type of interaction, feeding mode and trophic position. Furthermore, impact studies on microbes are relatively recent and predominantly focused on soil bacteria and fungi (Dawson and Schrama 2016). However, it is important to note that, since our focus was on field studies, our review may not have captured all the impacts on plant-soil feedbacks, which are often mediated by microorganisms, such as pathogens or symbionts. It is largely unknown how the strength of plant-soil feedbacks compares with plant-plant competition. This is an area of research which deserves more attention because such interactions influence the co-occurrence of native and invasive species (Lekberg et al. 2018).

Other areas of research interest might include the analysis of the major causes of the variation in impacts and improving their prediction. For this purpose, the information provided in our database could be associated with other aspects of biological invasions (Strayer 2012). For instance, links with their pathways of introduction (Pergl et al. 2017), their local or regional abundances (Bradley et al. 2019), the species traits and the biotic and abiotic characteristics of the invaded habitats (Pyšek et al. 2012; Sapsford et al. 2020) or their invasion history (Lenzner et al. 2022). The frequency and direction of impacts could also be compared to those of invasive animals and amongst invaded areas to determine taxonomic differences in impact across regions.

Causal impacts, together with the probability of arrival and establishment, is one of the main requested information to identify potential invasive species. Therefore,

from a management point of view, the database displays and harmonises the available peer-reviewed publications that can be used for horizon scanning to identify potential invasive species in countries where they are not yet present (e.g. Lucy et al. (2020); Cano-Barbacil et al. (2023)). The information from the database can also be used to populate standardised impact assessments, such as the EICAT-IUCN (Blackburn et al. 2014) and to assist species management prioritisation, based on the magnitude of their impacts on biodiversity.

From a policy perspective, it is important to highlight that, although our analysis screened all European countries, the database does not include information for 29 of the 39 invasive plant species of EU concern (European Union 2014, 2017). Moreover, of the 20 most studied species according to our database, only three are regulated, namely *Impatiens glandulifera*, *Heracleum mantegazzianum* and *H. sosnowskyi*. These mismatches can be explained by some of the features of the EU Regulation (Carboneras et al. 2018). Some regulated species are not yet present in the EU (e.g. many aquatic plant species), but, if introduced, would be capable of establishing self-sustainable populations. On the other hand, some species are present, form self-sustainable populations and cause significant adverse impacts on biodiversity and ecosystem services in Europe, but listing the species will not prevent, minimise or mitigate their impacts and are therefore not listed.

Conclusion

Our first comprehensive European database of the field studies reporting on the ecological effects of invasive non-native plants indicates that invasive plants cause impacts to species, communities and ecosystem processes of a wide range of taxa at different trophic levels. Major gaps in knowledge are found in Baltic and Balkan countries, in desert and semi-arid shrublands, subtropical forests and high mountains. To improve the knowledge of the impacts of invasive plant species, we also advocate for more studies on species that are still locally rare and with restricted distribution, and on how they modify plant-soil-microbe interactions.

The information provided in this database is of interest for academic, management and policy-related purposes at the national, European and international scale. We acknowledge that our database may not encompass all relevant studies. The Web of Science has been the most widely used database for bibliometric analysis, offering more comprehensive coverage of older literature compared to Scopus. However, Scopus includes a larger list of journals than the Web of Science (Mongeon and Paul-Hus 2016). Further extensions of the database should also include a broader keywords string. For example, although restoration studies may not be explicitly designed to detect impacts, they can offer valuable insights into ecological differences between invaded plots before and after intervention in removal plots. Our database will have to be updated as new field studies on the ecological impacts of invasive species are published.

Acknowledgements

We thank T. Heger, S. Jelaska and an anonymous reviewer for valuable comments on a previous version of this paper. We thank IPBES for inspiring the construction of this database. José M. Espinar assisted on data extraction.

This research was supported by the 2017–2018 Belmont Forum–BiodivERsA International joint call project InvasiBES under the BiodivScen ERA-Net COFUND programme and with the following funding organisations: the Spanish Ministry of Science and Innovation (PCI2018-092939, PCI2018-092986, MCI/AEI/FEDER, RED2022-134338-T) and the Swiss National Science Foundation (31BD30-184114 and 31003A_179491); also by EXARBIN (RTI2018-093504-B-100), RADIOPOPO (PDI2021-122690OB-100); the European Union FPS COST Actions FP1403 NNEXT; and through the European Regional Development Fund (SUMHAL, LIFEWATCH-2019-09-CSIC-4, POPE 2014-2020).

References

Bacher S, Galil BS, Nuñez MA, Ansong M, Cassey P, Dehnen-Schmutz K, Fayvush G, Hiremath AJ, Ikegami M, Martinou AF, McDermott SM, Preda C, Vilà M, Weyl OLF, Fernandez RD, Ryan-Colton E (2023) Chapter 4: Impacts of invasive alien species on nature, nature's contributions to people, and good quality of life. In: Roy HE, Pauchard A, Stoett P, Renard Truong T (Eds) Thematic Assessment Report on Invasive Alien Species and Their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn. https://doi.org/10.5281/zenodo.7430731

Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Marková Z, Mrugała A, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Sendek A, Vilà M, Wilson JRU, Winter M, Genovesi P, Bacher S (2014) A unified classification of alien species based on the magnitude of their environmental impacts. PLoS Biology 12(5): e1001850. https://doi.org/10.1371/journal.pbio.1001850

Bradley BA, Laginhas BB, Whitlock R, Allen JM, Bates AE, Bernatchez G, Diez JM, Early R, Lenoir J, Vilà M, Sorte CJB (2019) Disentangling the abundance-impact relationship for invasive species. Proceedings of the National Academy of Sciences of the United States of America 116(20): 9919–9924. https://doi.org/10.1073/pnas.1818081116

Cano-Barbacil C, Carrete M, Castro-Díez P, Delibes-Mateos M, Jaques JA, López-Darias M, Nogales M, Pino J, Ros M, Traveset A, Turon X, Vilà M, Altamirano M, Álvarez I, Arias A, Boix D, Cabido C, Cacabelos E, Cobo F, Cruz J, Cuesta JA, Dáder B, del Estal P, Gallardo B, Gómez Laporta M, González-Moreno P, Hernández JC, Jiménez-Alfaro B, Lázaro Lobo A, Leza M, Montserrat M, Oliva-Paterna FJ, Piñeiro L, Ponce C, Pons P, Rotchés-Ribalta R, Roura-Pascual N, Sánchez M, Trillo A, Viñuela E, García-Berthou E (2023) Identification of potential invasive alien species in Spain through horizon scanning. Journal of Environmental Management 345: e118696. https://doi.org/10.1016/j.jenvman.2023.118696

Carboneras C, Genovesi P, Vilà M, Blackburn TM, Carrete M, Clavero M, D'hondt B, Orueta JF, Gallardo B, Geraldes P, González-Moreno P, Gregory RD, Nentwig W, Paquet JY, Pyšek P, Rabitsch W, Ramírez I, Scalera R, Tella JL, Walton P, Wynde R (2018) A prioritised list of invasive alien species to assist the effective implementation of EU legislation. Journal of Applied Ecology 55(2): 539–547. https://doi.org/10.1111/1365-2664.12997

Carboni M, Guéguen M, Barros C, Georges D, Boulangeat I, Douzet R, Dullinger S, Klonner G, van Kleunen M, Essl F, Bossdorf O, Haeuser E, Talluto MV, Moser D, Block S, Conti L, Dullinger I, Münkemüller T, Thuiller W (2018) Simulating plant invasion dynamics in mountain ecosystems under global change scenarios. Global Change Biology 24(1): e289–e302. https://doi.org/10.1111/gcb.13879

Castro-Díez P, Godoy O, Alonso A, Gallardo A, Saldaña A (2014) What explains variation in the impacts of exotic plant invasions on the nitrogen cycle? A meta-analysis. Ecology Letters 17(1): 1–12. https://doi.org/10.1111/ele.12197

Castro-Díez P, Pauchard A, Traveset A, Vilà M (2016) Linking the impacts of plant invasion on community functional structure and ecosystem properties. Journal of Vegetation Science 27(6): 1233–1242. https://doi.org/10.1111/jvs.12429

Castro-Díez P, Vaz AS, Silva JS, van Loo M, Alonso Á, Aponte C, Bayón Á, Bellingham PJ, Chiuffo MC, DiManno N, Julian K, Kandert S, La Porta N, Marchante H, Maule HG, Mayfield MM, Metcalfe D, Monteverdi MC, Núñez MA, Ostertag R, Parker IM, Peltzer DA, Potgieter LJ, Raymundo M, Rayome D, Reisman-Berman O, Richardson DM, Roos RE, Saldaña A, Shackleton RT, Torres A, Trudgen M, Urban J, Vicente JR, Vilà M, Ylioja T, Zenni RD, Godoy O (2019) Global effects of non-native tree species on multiple ecosystem services. Biological Reviews of the Cambridge Philosophical Society 94(4): 1477–1501. https://doi.org/10.1111/brv.12511

Dawson W, Schrama M (2016) Identifying the role of soil microbes in plant invasions. Journal of Ecology 104: 1211–1218. https://doi.org/10.1111/1365-2745.12619

European Union (2014) Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species. OJ L 317, 35–55.

European Union (2017) Commission Implementing Regulation (EU) 2017/1263 of 12 July 2017 updating the list of invasive alien species of Union concern established by Implementing Regulation (EU) No 2016/1141 pursuant to Regulation (EU) No 1143/2014 of the European Parliament and of the Council. OJ L 182, 37–39.

Gallardo B, Clavero M, Sánchez MI, Vilà M (2016) Global ecological impacts of invasive species in aquatic ecosystems. Global Change Biology 22(1): 151–163. https://doi.org/10.1111/gcb.13004

Hulme PE, Pyšek P, Jarošík V, Pergl J, Schaffner U, Vilà M (2013) Bias and error in understanding plant invasion impacts. Trends in Ecology & Evolution 28(4): 212–218. https://doi.org/10.1016/j.tree.2012.10.010

IPBES (2018) The IPBES regional assessment report on biodiversity and ecosystem services for Europe and Central Asia. In: Rounsevell M, Fischer M, Torre-Marin Rando A, Mader A (Eds) Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, 892 pp. https://doi.org/10.5281/zenodo.3237429

IPBES (2023) Summary for Policymakers of the Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn. https://doi.org/10.5281/zenodo.7430692

Jeschke JM, Bacher S, Blackburn TM, Dick JTA, Essl F, Evans T, Gaertner M, Hulme PE, Kühn I, Mrugała A, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Sendek A, Vilà M, Winter M, Kumschick S (2014) Defining the impact of non-native species. Conservation Biology 28(5): 1188–1194. https://doi.org/10.1111/cobi.12299

Kueffer C, Daehler CC, Torres-Santana CW, Lavergne C, Meyer JY, Otto R, Silva L (2010) A global comparison of plant invasions on oceanic islands. Perspectives in Plant Ecology, Evolution and Systematics 12(2): 145–161. https://doi.org/10.1016/j.ppees.2009.06.002

Kumschick S, Gaertner M, Vilà M, Essl F, Jeschke JM, Pysek P, Ricciardi A, Bacher S, Blackburn TM, Dick JTA, Evans T, Hulme PE, Kühn I, Mrugala A, Pergl J, Rabitsch W, Richardson DM, Sendek A, Winter M (2015) Ecological impacts of alien species: Quantification, scope, caveats, and recommendations. Bioscience 65(1): 55–63. https://doi.org/10.1093/biosci/biu193

Kuznetsova A, Brockhoff PB, Christensen RHB (2017) lmerTest package: Tests in linear mixed effects models. Journal of Statistical Software 82(13): 1–26. https://doi.org/10.18637/jss.v082.i13

Lekberg Y, Bever JD, Bunn RA, Callaway RM, Hart MM, Kivlin SN, Klironomos J, Larkin BG, Maron JL, Reinhart KO, Remke M, van der Putten WH (2018) Relative importance of competition and plant–soil feedback, their synergy, context dependency and implications for coexistence. Ecology Letters 21(8): 1268–1281. https://doi.org/10.1111/ele.13093

Lenzner B, Latombe G, Schertler A, Seebens H, Yang Q, Winter M, Weigelt P, van Kleunen M, Pyšek P, Pergl J, Kreft H, Dawson W, Dullinger S, Essl F (2022) Naturalized alien floras still carry the legacy of European colonialism. Nature Ecology & Evolution 6(11): 1723–1732. https://doi.org/10.1038/s41559-022-01865-1

Lucy FE, Davis E, Anderson R, Booy O, Bradley K, Britton JR, Byrne C, Caffrey JM, Coughlan NE, Crane K, Cuthbert RN, Dick JTA, Dickey JWE, Fisher J, Gallagher C, Harrison S, Jebb M, Johnson M, Lawton C, Lyons D, Mackie T, Maggs C, Marnell F, McLoughlin T, Minchin D, Monaghan O, Montgomery I, Moore N, Morrison L, Muir R, Nelson B, Niven A, O'Flynn C, Osborne B, O'Riordan RM, Reid N, Roy H, Sheehan R, Stewart D, Sullivan M, Tierney P, Treacy P, Tricarico E, Trodd W (2020) Horizon scan of invasive alien species for the island of Ireland. Management of Biological Invasions : International Journal of Applied Research on Biological Invasions 11(2): 155–177. https://doi.org/10.3391/mbi.2020.11.2.01

Lüdecke D (2018) ggeffects: Tidy data frames of marginal effects from regression models. Journal of Open Source Software 3(26): e772. https://doi.org/10.21105/joss.00772

Marchante H, Freitas H, Hoffmann JH (2011) The potential role of seed banks in the recovery of dune ecosystems after removal of invasive plant species. Applied Vegetation Science 14(1): 107–119. https://doi.org/10.1111/j.1654-109X.2010.01099.x

Mongeon P, Paul-Hus A (2016) The journal coverage of Web of Science and Scopus: A comparative analysis. Scientometrics 106(1): 213–228. https://doi.org/10.1007/s11192-015-1765-5

Morente-López J, Arjona Y, Salas-Pascual M, Reyes-Betancort JA, del Arco-Aguilar MJ, Emerson BC, García-Gallo A, Jay-García LS, Naranjo-Cigala A, Patiño J (2023) Biogeographic origins and drivers of alien plant invasions in the Canary Islands. Journal of Biogeography 50(3): 576–590. https://doi.org/10.1111/jbi.14556

Pergl J, Pyšek P, Bacher S, Essl F, Genovesi P, Harrower CA, Hulme PE, Jeschke JM, Kenis M, Kühn I, Perglová I, Rabitsch W, Roques A, Roy DB, Roy HE, Vilà M, Winter M, Nentwig W (2017) Troubling travellers: Are ecologically harmful alien species associated with particular introduction pathways? NeoBiota 32: 1–20. https://doi.org/10.3897/neobiota.32.10199

Pyšek P, Jarošík V, Hulme PE, Pergl J, Hejda M, Schaffner U, Vilà M (2012) A global assessment of invasive plant impacts on resident species, communities and ecosystems: The interaction of impact measures, invading species' traits and environment. Global Change Biology 18(5): 1725–1737. https://doi.org/10.1111/j.1365-2486.2011.02636.x

R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Romero-Blanco A, Castro-Díez P, Lázaro-Lobo A, Molina-Venegas R, Cruces P, Pyšek P (2023) Searching for predictors of the variability of impacts caused by non-native trees on regulating ecosystem services worldwide. The Science of the Total Environment 877: e162961. https://doi.org/10.1016/j.scitotenv.2023.162961

Russell L (2018) Emmeans: estimated marginal means, aka least-squares means. R package version 2: 1–1.

Sapsford SJ, Brandt AJ, Davis KT, Peralta G, Dickie IA, Gibson II RD, Green JL, Hulme PE, Nuñez MA, Orwin KH, Pauchard A, Wardle DA, Peltzer DA (2020) Towards a framework for understanding the context dependence of impacts of non-native tree species. Functional Ecology 34(5): 944–955. https://doi.org/10.1111/1365-2435.13544

Silva L, Land EO, Luis J, Luengo R, Borges P, Oliveira P, Jardim R (2008) Invasive alien species in Macaronesia. In: Silva L, Land EO, Luis J (Eds) Invasive Terrestrial Flora & Fauna of Macaronesia. TOP 100 in Azores, Madeira and Canaries, Ponta Delgada, 159–165.

Simberloff D, Martin JL, Genovesi P, Maris V, Wardle DA, Aronson J, Courchamp F, Galil B, García-Berthou E, Pascal M, Pyšek P, Sousa R, Tabacchi E, Vilà M (2013) Impacts of biological invasions: What's what and the way forward. Trends in Ecology & Evolution 28(1): 58–66. https://doi.org/10.1016/j.tree.2012.07.013

Strayer DL (2012) Eight questions about invasions and ecosystem functioning. Ecology Letters 15(10): 1199–1210. https://doi.org/10.1111/j.1461-0248.2012.01817.x

Vilà M, Hulme PE (2017) Impact of Biological Invasions on Ecosystem Services. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-45121-3

Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, Pergl J, Schaffner U, Sun Y, Pyšek P (2011) Ecological impacts of invasive alien plants: A meta-analysis of their effects on species, communities and ecosystems. Ecology Letters 14(7): 702–708. https://doi.org/10.1111/j.1461-0248.2011.01628.x

Vilà M, Gallardo B, Preda C, García-Berthou E, Essl F, Kenis M, Roy HE, González-Moreno P (2019) A review of impact assessment protocols of non-native plants. Biological Invasions 21(3): 709–723. https://doi.org/10.1007/s10530-018-1872-3

Vimercati G, Kumschick S, Probert AF, Volery L, Bacher S (2020) The importance of assessing positive and beneficial impacts of alien species. NeoBiota 62: 525–545. https://doi.org/10.3897/neobiota.62.52793

Vitousek PM, Walker LR (1989) Biological invasion by Myrica Faya in Hawai'i: Plant demography, nitrogen fixation, ecosystem effects. Ecological Monographs 59(3): 247–265. https://doi.org/10.2307/1942601

Volery L, Jatavallabhula D, Scillitani L, Bertolino S, Bacher S (2021) Ranking alien species based on their risks of causing environmental impacts: A global assessment of alien ungulates. Global Change Biology 27(5): 1003–1016. https://doi.org/10.1111/gcb.15467

Supplementary material 1

Supplementary information

Authors: Montserrat Vilà, Alejandro Trillo, Pilar Castro-Díez, Belinda Gallardo, Sven Bacher

Data type: docx

Explanation note: **table S1.** Definitions of the response variables used to classify impact types on native species (i.e. individuals of the same taxon) and communities (i.e. individuals of several species at a site). **table S2.** Publication level information in PLANTIMPACTSEUROPE_publicationLevel. xlsx. The PLANTIMPACTSEUROPE database can be accessed at https://figshare.com/s/0a890d22bf5632fe5cb5. **table S3.** Invasive plant information and field studies testing for impacts in PLANTIMPACTSEUROPE_impactsDatabase. xlsx. The PLANTIMPACTSEUROPE database can be accessed at https://figshare.com/s/0a890d22bf5632fe5cb5. **Storage location and medium:** The PLANTIMPACTSEUROPE database can be accessed at https://figshare.com/s/0a890d22bf5632fe5cb5. (1) PLANTIMPACTSEUROPE_publicationLevel. xlsx: 266 publications with indication of countries, habitats and study locations, 312 entries (rows excluding the header), 8 columns, 59 KB. (2) PLANTIMPACTSEUROPE_impactsDatabase. xlsx: 4259 impacts (rows excluding the header), 16 columns, 348 KB.

Link: https://doi.org/10.3897/neobiota.90.112368.suppl1